AFFDL-FDCC-TM-66-5
September 1966

AD 653340

HANDLING QUALITIES AND PILOT WORK LOAD

by

C.B. Westbrook, R.O. Anderson, and P.E. Pietrzak
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio

Introduction

This paper has the objective of defining the relationship between handling qualities and pilot stress and workload. The reasons underlying the importance of pilot workload measurement are discussed and ways to analyze or treat pilot vehicle systems are reviewed. The various measures of pilot workload that have been used or considered are discussed and some new data on the possible use of pupil dilation as a measure of stress are presented.

The pilot of a flight vehicle performs a range of tasks and combinations of tasks between take off and landing. These run a gamut from the most simple to those single or multiple axis tasks that may tax his capabilities to the limit. In preparation for the flight, certain planning and evaluation functions are performed by the pilot. In take off and in other phases of flight such as formation flying, terrain avoidance, rough air situations, gunnery runs, and approach and landing, the pilot performs as a precision tracker. The difficulty of his tracking task obviously varies widely as a function of the basic dynamics of his vehicle at the time, the condition or availability of any augmentation system or display aids, and the disturbing inputs. The pilot

devotes as much effort to these tracking tasks as he feels necessary for efficiency or safety. In difficult control or emergency situations the pilot may regress to become a single axis tracker and ignore other control axes or piloting functions that are less demanding.

During the cruise phase of flight the pilot becomes in many cases a monitor and decision maker. It is clear that, in general, the pilot operates in a sampling manner, collecting information on various situations in flight, evaluating their significance, making decisions, and taking action or not as circumstances require. In certain situations such as engine or stability augmentation failure, the pilot may call on a repertoire of learned behavior that allows more rapid response to these situations.

The pilot and the stability and control engineer have, in many cases, used the term handling qualities to describe the degree of piloting ease or difficulty over the wide range of conditions, tasks, and situations that the pilot is faced with. The pilot opinion ratings collected integrate these diverse factors. It should not be unexpected that these ratings might vary over a wide range unless conditions of the test are very carefully controlled.

Work Load And Its Implications

It is well known that in some aircraft and in some flight conditions or emergencies that the pilot must work to the limit of his ability. Up to this limit it is also well known that if he desires he can maintain

his performance of a task even though complaining bitterly, a factor that prompted McRuer to refer to him as the "Vocal Adaptive Controller" (Reference 1). To a pilot the multiple stresses of flight, his workload, are summarized unde his judgment of the handling qualities.

The handling qualities engineer has endeavored to find a more analytical approach to specification of pilot workload and to correlate the pilot opinion rating with such an approach. The critical task philosophy, Reference 2, offers promises of at least bounding the limits of the problem.

The psychologists have, in general, taken a more academic approach to the problem. Experiments have been run with various side tasks and problem solving situations. Many of the experiments offer relatively little realism to the actual flight situation and the piloting job. Consequently much of this work has had limited application to practical system design other than in establishing trends or limits.

If a reliable method were available to obtain a measure of workload or stress, it is undoubtedly true that many of the anomalies in handling qualities data could be explained. As an example, Reference 3 reports combat tracking errors three or four times greater than those obtained under otherwise identical tracking tasks in test conditions. The implications on criteria for the design of new aircraft, their control systems and their display instrumentation are obvious. The systems could be designed analytically or tested under realistic simulation conditions. The design could provide a reasonable safety margin in pilot workload and yet take advantage of his capabilities where these

are available and may save some weight and cost in the aircraft, improve reliability or maintainability, etc. And yet this capability of measuring, and understanding overall pilot workload and thereby being able to utilize this knowledge in vehicle design continues to elude us.

Ways to Analyze or Treat Systems

The design of the cockpit display system in the past has been heavily intuitive with great reliance placed on simulation using a "cut and try" approach. To attempt to put the display design process on a more rational basis a methodology has been evolved. Reference 4 outlines a set of procedures which is often called time line analysis, although the complete methodology involves more than time line analysis, per se. Figure 1 taken from Reference 4 illustrates the process. Figure 2 illustrates a typical time line assignment chart with allocation of tasks to the crew members or the machine on a second by second or minute by minute basis as required. The process of determining the human workload under this procedure involves many small judgments and probably represents a considerable improvement over a broad intuitive decision or a "cut and try" simulation. Once preliminary time line charts are drawn and problem areas isolated, the process can be iterated with finer detail if necessary.

Another relatively new approach to flight control system analysis is the dynamic analysis of the pilot and the combined aircraft-autopilot system. The resulting pilot-vehicle system can then be evaluated with

respect to the adequacy of the airframe, or airframe-autopilot, dynamics for specific flight conditions. This approach, of course, requires the definition of some form of mathematical model of the pilot. This subject is covered in somewhat more detail in the next section, but for now the point is that pilot-vehicle analyses can be, and are being, made. The general approach is to: a. define and verify a mathematical model of the human operator for specific control tasks, b. define a set of "adjustment rules" that establish the numerical values associated with the pilot model for specific tasks, c. establish fundamental pilot limitations that constrain the adjustment ranges of the model parameters, and d. use all of the previous to predict the combined pilot-vehicle dynamics for the specific task in question. Reference 5 contains a brief description of this general approach.

From a practical standpoint, the workload related factors in this general pilot-vehicle analysis method include the constraints on the adjustment ranges of the model parameters. That is, the task exceeds the maximum pilot capability (full workload) if control of the airframe-autopilot combination requires the adjustment of pilot model parameters <u>beyond</u> known human limitations. Therefore, the parameter limitations or constraints may be considered workload measurements in this case, and subsequent application via the pilot-vehicle analysis method can yield: a. an analytical prediction of the pilot-vehicle system stability, b. some indication of closed-loop system performance,

c. an evaluation of the suitability of the airframe-autopilot system, and d. an insight into the vehicle-autopilot dynamic properties that are causing any problems, with attendant specification (handling qualities) implications.

The pilot-vehicle analysis approach outlined above has been extended to a design procedure called Pilot-Controller Integration or PCI, Reference 6. This procedure represents a systemmatic design method that considers control system failures as well as nominal performance. The procedure leads to a high flight-safety design. Figure 3 depicts the PCI process (from Reference 6), and workload measures are used in phases called "Failure Analysis by Paper and Pencil Methods" and "Failure Analysis by Simulation Methods." Specifically, a workload related measure is used in an "additive" fashion to determine if manual control under failed conditions is possible (normal workload plus incremental workload due to a system failure does not exceed maximum capability). If a failure results in a workload level above maximum capability, system design changes are made to either reduce the total workload, or decrease the probability of occurrence of the particular failure mode in question. The value of this process, in one particular case, is demonstrated in Reference 7 where the manhours invested in the application of the PCI process would be "recovered" through flight safety improvements in 8.8 aircraft flight hours.

The above methods of system analysis that require some measure of workload, or a related parameter, are for the most part theoretical

in nature. However, within the present state-of-the-art these approaches can be applied only to relatively simple, though perhaps important, cases. On the other hand, the complexities of modern flight vehicles dictate the use of simulators as both system analysis tools and experimental devices to validate the more theoretical approaches.

When simulation is used as a system analysis tool, the concepts of workloading may be more implicit than analytical approaches, but nonetheless they are still present. For example, when a multi-task mission phase is simulated, the "full workload" point is reached, or exceeded, when the subject cannot cope with the multitude of duties he is supposed to perform. Complete simulations should, therefore, include all task loadings including those related to stability and control as well as navigation, communication, and other functions. Under less severe conditions, simulation studies can still yield, or utilize, a measure of workload in the form of pilot rating to evaluate various alternative designs. This measure, related to workload (as discussed later), can be used in many multi-task situations, and with suitable rating procedures, quantitative as well as qualitative results can be obtained.

In summary, workload or a related measure plays an important role in a number of system analysis methods. The terminology in each case might be quite different, but a broad interpretation of "workload" is applicable in each instance.

Workload Prediction and Manual Control Theory

Over the past decade, a rather extensive body of literature relating to manual control theory has been produced (e.g. Reference 8). In fact, bibliographies are available in the area (Reference 9). Therefore, no attempt will be made here to summarize the current status. Instead, only the relationship between current theory and pilot workload prediction will be considered.

For a single compensatory tracking task (see Figure 4) existing theory is quite adequate to predict an operator's ability to control linear systems with random appearing inputs. That is, the limit of the operator's capability can be fairly accurately predicted. In terms of workload this represents the "full workload" case. On the other hand, the current theory cannot accurately predict a "workload" measure in the "gray" area where control is possible but of varying "difficulty". Within this gray area pilot opinion ratings have been, and are being, used as a measure of task difficulty.

Reference 7 contains an interesting correlation of pilot opinion ratings and workload measured with a side-task. Although the population size of the data presented is small, very good correlation is indicated. This encouraging result suggests that if pilot opinion ratings could be predicted from human response theory, one could in turn predict a workload level for a given task. A current U.S. Air Force sponsored research

program, investigating the tie between pilot opinion ratings and mathematical models of the human operator in specific tasks, may resolve this problem.

It should be emphasized, however, that predicting pilot workload, or some related measure, for a single task is only part of the overall problem. To use this information in system design as discussed above, the "additive" effects of several tasks must also be predicted. This is by no means easy. For example, the "additive" properties of pilot opinion ratings in multiple task situations (Reference 10) are relatively unknown. However, the results of recent attempts (e.g. Reference 11) to define mathematical models of the human operator in multi-axis tracking tasks may, again, provide the answer if pilot opinion ratings can be predicted from the resulting models.

All of the above discussion concerns compensatory tracking tasks. It is seen that even in this area, where probably the most useful and extensive body of human response theory exists for flight control applications, the prediction of workload or a related measure still poses a problem Because of this fact, it is not surprising that the situation is eve worse with respect to other piloting tasks, or combinations of tasks. This is, in fact, the reason why experimental simulation procedures are the most popular form of workload measurement technique at the present time.

Although a truly useful overall mathematical model of the human operator is a long way off at this time, attempts are being made to

formulate such a model. In this respect, certain human "subsystems" such as the eye movement servo and the hand control system (e.g. References 12 and 13) have been investigated and mathematical models formulated. These "subsystem" models vary in complexity, but Figure 5 taken from Reference 12 is a typical representation. It comes as no surprise that Figure 5 expanded to include all of the human operator subsystems important to piloting tasks would represent an extremely complex representation of the known complex human operator. Yet, each subsystem, and combination of subsystems, affects the overall workload of the human operator in a given task to some extent.

Some of the more recent attempts to provide broader models of the human operator are reported in References 14, 15 & 16. In Reference 14, Krendel and McRuer propose a "Successive Organization of Perception" (SOP) model of the human operator in tracking tasks that accounts for various methods, or modes, of control involved in skill development. Vossius, in Reference 15, discusses eye and hand models, and Vossius is currently considering an integrated model of visual perception, hand control, and alternate modes of control along the SOP lines. Finally, Senders, Elkind, and Smallwood in Reference 16 have proposed a visual sampling model that perhaps can be used in tracking as well as monitoring tasks. Each of the above developments represents an extension or expansion of simpler "subsystem" models toward a broader picture of the human operator.

In summary, manual control theory shows promise as a means to predict workload for, at least, certain combinations of piloting tasks. In addition, continued advances in the physiology of human subsystems may provide even more refined methods for more complex tasks. However, at the present time experimental simulator measurements, on an ad hoc basis, represent the most practical means to determine pilot workload in complicated flight control tasks.

Measures of Pilot Work Load

Figure 6 taken from Reference 17, presents a view of the factors involved in physiological measurements. The subject reacts to the various input factors which include the sustaining and sensory factors shown. In addition the subject reacts to psychological factors that are regenerated within himself from stored past experience. This is indicated by what is termed in this reference, the re-entrant loop. These are the factors of anxiety, fatigue, stress, the reflex, inherent, and learned behavior patterns, motivation, attitude, etc. The subject's output is divided into two basic classes, physiological and psychological with an intermediate or "gray" area in between. The division into classes does not occur neatly since it is known to laymen as well as physiologists that the body reacts to stress in many ways. An aroused individual's heart pounds, stomach contracts, bladder relaxes, adrenalin increases, pupils dilate, etc. These effects illustrate the complexity of the feedbacks within the human. However, for the purpose of normal measurement of pilot workload this strictly physiological class has not and is not expected

to be particularly helpful. This includes such measures as heart activity, electro-cardiograms, blood pressure and flow measurements, respiration, and metabolism measurements.

The normal pychological measures relate to operator behavior. One of the normal measures is that of performance in a tracking or problem solving task where a scoring system is devised. This scoring might be based on time on target, rms error, etc. Psychological experiments are usually run with large number of subjects with the tasks planned so as to allow statistical analysis techniques to be applied. Side tasks along with the primary task have been used in a number of cases. The idea is to consider a reduction in side task performance as an indication of an increase in primary task difficulty. These side tasks might be flashing lights or horns to be turned off at intervals or simple arithmetic or other problems to be solved. Eye motion studies have been used in a number of display oriented studies to determine the areas of concern to the pilot, the time spent on a particular instrument, and the links between various instruments. Psychologists also use questionnaires although they have been suspicious of and generally have avoided ratings scales.

The handling qualities engineer has placed less reliance on performance in his situation or flight tests. Measures such as average clearance in terrain flying, miss distance, or average error in tracking a target, of course, would be used where such criteria were

meaningful. This attitude towards less reliance on performance springs from his knowledge of the wide adaptability of the pilot to keep his performance constant in spite of varying degrees of difficulty of the task. He has tended to place his reliance on pilot opinion ratings. Furthermore, he has tended to avoid the use of large numbers of subjects, for cost reasons partially, but also because of a preference or a greater confidence in the results from a "calibrated" test pilot. This reliance on a small, especially selected statistical sample of subjects has spawned a running argument between psychologists and engineers over the validity of each other's data. The engineer has begun to put reliance, for specialized problem evaluation at least, on analyses of the pilot vehicle combination by means of describing function data on the human pilot. This has been touched on previously in this paper.

Between the strict physiological class of measures and the psychological class is the so called intermediate class. Included in this class are a number of measurements that are interesting to physiologists but also may be of use to the psychologist and the engineer. To this date, however, they have been of little use to the handling qualities engineer. One of these measures is the electrical potentials in the nervous system or the muscles. The electrical activity of the brain can be detected with electrodes and this is referred to as electroencephalography. The highly amplified records are called EEG's. These records are complex and by no means fully understood. Although not completely reliable as yet, important behavioral patterns such as

a subject's state of alertness and whether his eyes are open or shut can be monitored.

When individual muscles contract they exhibit potential changes that can be measured. This is referred to as electromyography and the records are called EMG's. These records can indicate the state of synchronism of body patterns and may be used to show the presence of fatigue. Some consideration has been given to the use of myoelectric signals for certain control system applications.

Also of the same type are measurements of the heart's activity (ECG) which has been referred to previously under the strictly physiological class of measurements.

Another general technique, referred to as galvanic skin response, (GSR), involves measurement of the resistance between two electrodes on the skin to the passage of a small current. This resistance is affected by the action of the near surface capillaries and the sweat glands, which of course are responsive to the nervous system. This measurement has potential usefulness as an index of a number of psychological states, degree of alertness, apprehension, fear, panic, and placidity. The system has its problems both in obtaining reliable signals and then in sorting these signals out, but to date this measurement has been the best measurement available for determining the psychophysiological performance of a subject.

As noted previously, dilation or constriction of pupils as a result of stress had been noted by the physiologists but little investigation or use has been made of the phenomenon. In Reference 18, Dr.

Eckhard Hess presents some very interesting observations of the reactions of the pupils to interest, emotions, attitude, and thought processes. Figure 7 shows averaged increases in pupil size for five subjects performing mental multiplications of varying difficulty. Dr. Hess refers to the eye as an extension of the brain, embryologically and anatomically, and furthermore, an extension that is in plain sight for the psychologist or engineer to peer at. Intuitively, it is felt that the possibilities of a useful measure of pilot workload are higher in this case, than for such measures as EEG or GSR where measurement problems, confusion in signals, and involved feedback loops are involved. Stimulated by Dr. Hess's work, which was not concerned with piloting or tracking situations, a preliminary experiment was performed to determine whether pupilometrics offered a measure of workload that we engineers and psychologists could use. The experiment and its general results are described below.

Pupil Dilation Experiments

The main objectives of the experimental program were: a. to determine if pupil size variations (similar to those reported in Reference 18) exist when tracking tasks of varying difficulty are performed, and b. to determine how these variations, if any, are correlated with task "difficulty" and "conventional" workload measurements.

To accomplish these objectives a low order, but difficult, manual tracking task with an unstable first order controlled element was

simulated. The subject's eye was photographed using available artificial light and a 16mm. motion picture camera. Strip chart recordings of appropriate signals were made at the same time. To synchronize the eye data with the strip chart recordings, the camera photographed the subject's eye along with a small voltmeter that displayed a measure of task difficulty and computer start and stop signals. A secondary side-task was also implemented on the same analog computer used to simulate the controlled element dynamics. This side-task was used to provide a "conventional" measure of workload. The two tasks are described below:

Tracking Task: Representing the pilot's input stick deflection by c, and the controlled element output by m, the controlled element differential equation was $\frac{dm}{dt} - \lambda m = \lambda c$, where $\frac{dm}{dt}$ = time derivative of m(t). The value of λ, in rad/sec, controls the degree or "difficulty" of the tracking task, and the value could be held constant or varied as a f ction of time. In the latter case, the parameter λ varied at a rate of .10 rad/sec^2 from an initial 3.0 value until the tracking error (-m) on the oscilloscope display reached a value of $\pm$ 2 cm. At this point, the λ rate was switched to a value of .025 rad/sec^2 until control was lost (first time an error of $\pm$ 7 cm on the scope was reached). The subject could see a region of about $\pm$ 6 cm. on the scope. The time-varying case is called a "critical" task in Reference 2, and the minimum value of $\frac{1}{\lambda}$ reached by the subject is a good measure of his effective reaction time delay in this tracking task. In the present case, however, the task served as a "ramp" loading that pushed the subject to his limits (full workload).

The tracking error (-m) was displayed to the subject as a horizontally moving dot on the display, and control was achieved by moving a vertically mounted side-stick controller with a left-to-right wrist motion. The controlled element had no external input, and therefore the system output was a result of pilot actions only. In all cases the subject was told to keep the dot centered on the scope with a minimum of error.

Side-Task: The side-task used was a version of that described in Reference 7 for "conventional" workload measurements. This task consisted of centering a horizontal line on a second display scope adjacent to the tracking task display scope. A random noise source triggered the "line" from a zero setting to a plus (up) or minus (down) position in a random fashion at an average rate of about 3.25 seconds between inputs. The subject used a three position trim switch in his left hand to generate a pulse that would return the "line" to zero. Once triggered by the random noise, the line would hold the off-zero setting until the subject responded. The absolute value of the displayed signal was integrated over time, and a "score" (T) was obtained as the integrated value divided by the product of the number of random triggering signals that occurred during a given run and the offset voltage value. The measured score was, therefore, proportional to the subject's average time delay in responding to the side-task. During experiments with the subject operating both the tracking task and the side-task, the subject was told to give the tracking task the highest priority, and respond to the side-task only when possible.

The specific experiments performed consisted of four classes:

1. Time-varying λ tracking.
2. Fixed λ tracking (various λ values).
3. Fixed λ tracking with side-task.
4. Error observation only, no other tasks.

The latter was accomplished by recording the tracking error during experiments in the first and second classes with an FM tape recorder, and then reproducing the output for the same subject to observe. Photographs were taken in each case. For each class the general experimental arrangement is shown in Figure 8.

Although several subjects have participated in the experiments made to date, the results presented here were obtained with a single subject. This subject, a rated pilot, has a nominal amount of experience with tracking tasks and simulators in general, and a fair amount of experience with the tracking task used here. In the latter experiments reported, he obtained time-varying λ values of about 6.5 rad/sec which approached the values of very experienced subjects as reported in Reference 2. Perhaps the most dramatic results of the experiments are shown in Figure 9 where error, λ, and eye variations in the form of pupil diameter to iris diameter ratios (R) are given for a time-varying λ experiment (Class 1). In addition, R values for constant λ's (Class 2) are superimposed, using the symbol $\mapsto$, on the R plot at the time point corresponding to each λ. Figure 9 indicates a large variation in R (about 36%) over

the 46 second run. Furthermore, the R variation is seen to exhibit a steady increase with increased λ (increasingly more "difficult" task) as well as rapid increases that are directly correlated with the envelope of error. That is, R increases (pupil dilation) with large error excursions at points in the run where the subject almost loses control. Finally, the constant λ values of R (from data recorded shortly before the time-varying run shown) evidence the same general steady increase in R up to a λ value of about 5.2 rad/sec. The fluctuations in the R data, with about a two second period, may be due to measurement errors in reducing the camera data (data points taken at about one second intervals). Or, these variations may be "unrest" fluctuations of the type reported in Reference 19.

The results of a series of Class 3 runs are compared with eye measurements from a series of Class 2 runs for the same fixed values of λ in Figure 10.

The data are average values for one 30 second tracking task run, and two 60 second tracking plus side-task runs for each λ. The workload measurement, T, increases as the primary tracking task becomes more difficult (λ increases). Above a λ value of 4.9 rad/sec, a leveling off and scatter is observed in the data. This may be due to nonlinear variations with λ, or perhaps training effects are involved. At any rate, the R variation with λ is much the same as the T variation indicating a direct correlation of increased "conventional" workload with pupil dilation. Above λ = 5.5 rad/sec values, however, the data do not

show similar trends in R and T. Again training effects may be evident, or the small data population may be the answer to this difference.

In an attempt to determine if the pupil ations observed were the direct results of observing the display only, and not unique to the combined observation-control task, a limited amount of data was collected from Class 4 experiments. Figure 11 shows data from the last 20 seconds of a time-varying λ experiment in the form of R values during actual tracking, and when the subject is simply observing the same error signal. A difference in the R values at coincident times is evident up to the last few seconds of the experiment. Film records also indicated much more eye blinking, and some eye tracking, in the monitoring record. The tracking record showed a steady "stare". It should be noted, however, that a higher speed, and grainy, film used in the run shown caused data reduction problems and associated scatter in the data.

Finally, a number of Class 1 experiments with a variety of subjects with very little training showed a quite universal effect, with R ratio increases from near zero to 20% over the time-varying λ runs.

Although the experiments reported here are certainly preliminary, the main objectives were met, and the following tentative conclusions can be drawn:

a. Pupil dilation is evident in certain manual tracking tasks of increasing "difficulty".

b. This dilation is correlated with the results of at least one, more or less conventional, workload measurement technique, and is also correlated with task "difficulty".

c. The exact cause of this effect is unknown, but it does not appear to be the sole result of error observation. That is, the phenomenon appears to be a result of stresses from the combined observation-control task.

Much remains to be done before pupil size variations can be used with confidence as a manual control workload measurement technique, but the preliminary results reported here are encouraging. Furthermore, the advantages of the method, if verified by further work, over side-task methods are clear with respect to rapid response, the degree of subject distraction from the main task, and the possibility of electronic on-line data reduction (e.g. Pupilometer of Reference 19).

Conclusions and Recommendations

In conclusion it can be said, without fear of contradiction, that there is a real need for consideration of workload in setting the requirements for and specifications of pilot related aircraft parameters. Once available, quantitative measures of workload would play a very important role in the design of the aircraft and its flight control system. The benefits would be real and important.

It has been pointed out that there are a number of methods to measure some workload related parameters, none of which have been very generally useful or widely applied. Human response theory and physiology developments may provide methods to predict work loading for certain control related tasks; however, at present, experimental simulation procedures are the most useful.

A new workload related measurement technique, based on pupil dilation, is shown to have some promise from preliminary experiments. The method is applicable to flight control tasks, provides rapid response, and presents no subject distraction. Additional, more extensive, and more carefully planned experiments are definitely in order to explore the possibilities.

There is no question but that the handling qualities engineer should broaden his ideas of workload and make a concentrated effort to apply the ideas and measurement tools of the physiologist and the psychologist to the quantitative measurement of workload. The need is clear and the possibilities are apparent. The time is opportune for those in research to take action.

References

1. Ashkenas, I.L. & McRuer, D.T., "The Vocal Adaptive Controller-Human Pilot Dynamics and Opinion," Systems Technology, Inc., 1960

2. Jex, H.R., McDonnel, J.D., and Phatak, A.V., "A 'Critical' Tracking Task for Man/Machine Research Related to the Operator's Effective Delay Time", Systems Technology, Inc. Paper No. 44, presented at the MIT-NASA Working Conference on Manual Control, Feb 28 - March 2, 1966

3. Infanti, N. & Newell, F., "Air to Ground Tracking with Linear and Nonlinear Yaw Damping," Cornell Aeronautical Laboratory Report GM 776-T-55, January 1956

4. "Whole Panel Control Display Study," prepared by Lear, Inc., ASD TR 61-91, Vol. I & II, July 1960

5. McRuer, D.T. & Krendel, E.S., "The Man-Machine System Concept," Proceedings of the IRE, Fifth Anniversary Issue, Vol. 50, No. 5, May 1962

6. Cole, G., et al, "Study of Pilot-Controller Integration for Emergency Conditions," RTD TDR 63-4092, Minneapolis-Honeywell Regulator Company, 1964

7. Gaul, John W., "Application of Pilot-Controller Integration Techniques to a Representative V/STOL Aircraft," AFFDL TR 65-200, Bell Aerosystems Company, October 1965

8. McRuer, D.T.; Graham, D.; Krendel, E. & Reisener, W., "Human Pilot Dynamics in Compensatory Systems," AFFDL TR 65-15, Systems Technology, Inc. and The Franklin Institute, July 1965

9. Summers, L.G. & Zeidman, K., "A Study of Manual Control Methodology With Annotated Bibliography," NASA CR-125, November 1964

10. Dander, V.A. Capt., "An Evaluation of Four Methods for Converting Single-Axis Pilot Ratings to Multi-Axis Pilot Ratings Using Fixed Base Simulation Data," Air Force Institute of Technology Thesis, GE/EE/62-4, December 1962

11. Levison, W.H. & Elkind, J.E., "Studies of Multi-Variable Manual Control Systems," BBN Report No. 1339, Bolt Beranek and Newman, Inc., January 1966

12. Stark, Lawrence; Kupfer, Carl & Young, Lawrence R., "Physiology of the Visual Control System," NASA Report CR-238, Biosystems,Inc., June 1965

13. Young, Lawrence R. & Stark, Lawrence, "Biological Control Systems - A Critical Review and Evaluation," NASA Report CR-190, Biosystems,Inc., March 1965

14. Krendel, E.S. & McRuer, D.T., "A Servomechanisms Approach to Skill Development," Journal of The Franklin Institute, Vol. 269, No. 1, January 1960

15. Vossius, G., "Systemtheoretische Untersuchungen Der Willkurbewegung" (System Theoretical Investigations of the Random Movement), Aus dem Institut fur Animalische Physiologie der Universitat Frankfurt/M, 1962

16. Senders, J.W.; Elkind, J.I. & Smallwood, R., "An Investigation of the Visual Sampling Behavior of Human Operators," Bolt Beranek and Newman, Inc. Report No. 1246, 10 May 1965

17. "Techniques of Physiological Monitoring", AMRL-TDR-62-98, Vol. I Fundamentals, Vol II Components, Volume III Systems

18. Hess, Eckhard H., "Attitude and Pupil Size", pp 46-54, Scientific American, April 1965.

19. Stark, Lawrence, "Stability, Oscillations, and Noise in the Human Pupil Servomechanism", Proceedings of the IRE, November 1959

Additional References of Interest

20. Monty, R.A., Obermaier, J.E., & Rieley, W.J., "A Bibliography of Research on Human Tracking Performance", Cornell Aero Lab Report CAL 131

21. Ruby, W.J., and Month, R.A., "Human Tracking Ability for Maximum Terrain Following," Cornell Aero Lab Report IH1715-E-5, August 1963

22. Ruby, W.J. & Month, R.A., "Human Tracking Ability for Maximum Terrain Following With Added Workload," Cornell Aeronautical Lab Report UB 1813-E-5

23. Soliday, S.M., "Effects of Task Loading on Pilot Performance During Simulated Low Attitude High Speed Flight," TRECOM TR 64-69

24. Brown, J.L., Kuehnel, H., Nicholson, F.T., & Flutterweit, A., "Comparison of Tracking Performance in the TV-2 Aircraft and the ACL Computer/AMAL Human Centrifuge Simulation of This Aircraft," U.S. Naval Air Development Center Report NADC MA 6016/NADC-AC-6008, 7 November 1960

25. Wasicko, R.J., & Magdaleno, R.E., "Effects of Non-Linearities on Human Operator Tracking Performance, A Review of the Literature," AMRL TR 65-158, Systems Technology, Inc., October 1965

26. Jex, H.R., Cromwell, C.H. & Siskind, R.K., "Correlation of Experimental and Theoretical Limits for Pilot Control of Unstable Second Order Systems," Systems Technology, Inc. TM 56, July 1960

27. McRuer, D.T., Ashkenas, I.L. & Guerre, C.L., "A Systems Analyses View of Longitudinal Handling Qualities," WADD TR 60-43, January 1960

28. McRuer, D.T., Weir, D.H., Jex, J.R., Wolkovitch, J., Moore, G.P., & Hofman, L.G., "Collection and Compilation of New Approaches to Human-Pilot/Vehicle Dynamic Analysis," Systems Technology, Inc. Technical Report 164-1, July 1966

29. Weisz, A.Z. & McElroy, L.S., "Information Processing in a Complex Task Under Speed Stress," ESD TDR 64-391, May 1964

30. Obermayer, R.W. & Muckler, F.A., "Performance Measurement in Flight Simulation Studies," NASA CR 82, July 1964

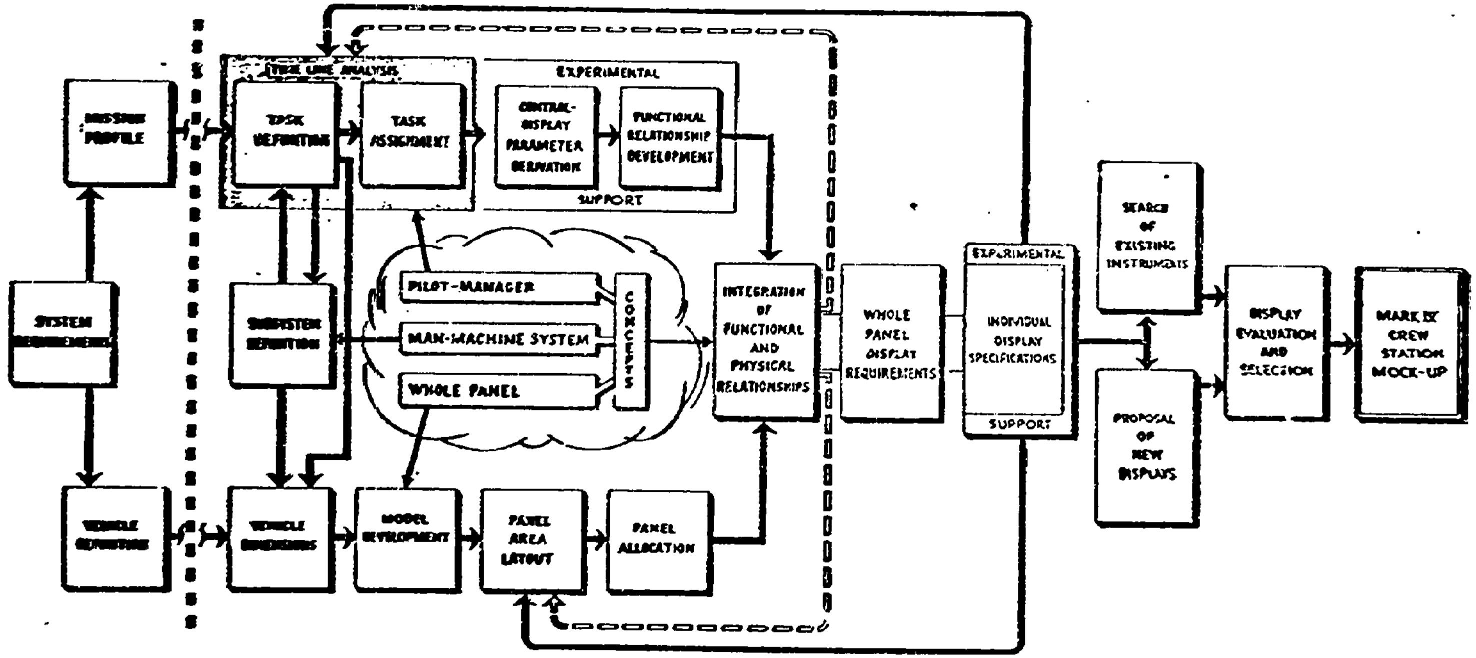
31. Garvey, W.D. & Henson, J.B., "Interactions Between Display Gain and Task Induced Stress in Manual Tracking Systems", NRL Report 5204, October 8, 1958

32. Senders, J.W., Kristofferson, A.B., Levison, W., Dietrich, C.W. & Ward, J.L., "An Investigation of Automobile Driver Information Processing," Bolt Beranek and Newman Report 1B35, April 1966

33. Senders, J.W., Elkind, J.I., Gringnetti, M., & Smallwood, R., "An Investigation of the Visual Sampling Beahviour of Human Observers," NASA CR 434, April 1966

34. Ekstrom, P., "Analyses of Pilot Work Loads in Flight Control Systems With Different Degrees of Automation," IRE Professional Group on Human Factors in Electronics, May 1962

35. Lindquist, O.H. & Gross, R.L., "Human Engineering Man Machine Study of a Weapon System," Minneapolis-Honeywell Aero Report, R-ED 6094, October 1958



DEVELOPMENT PROCEDURE CHART
FIGURE 1

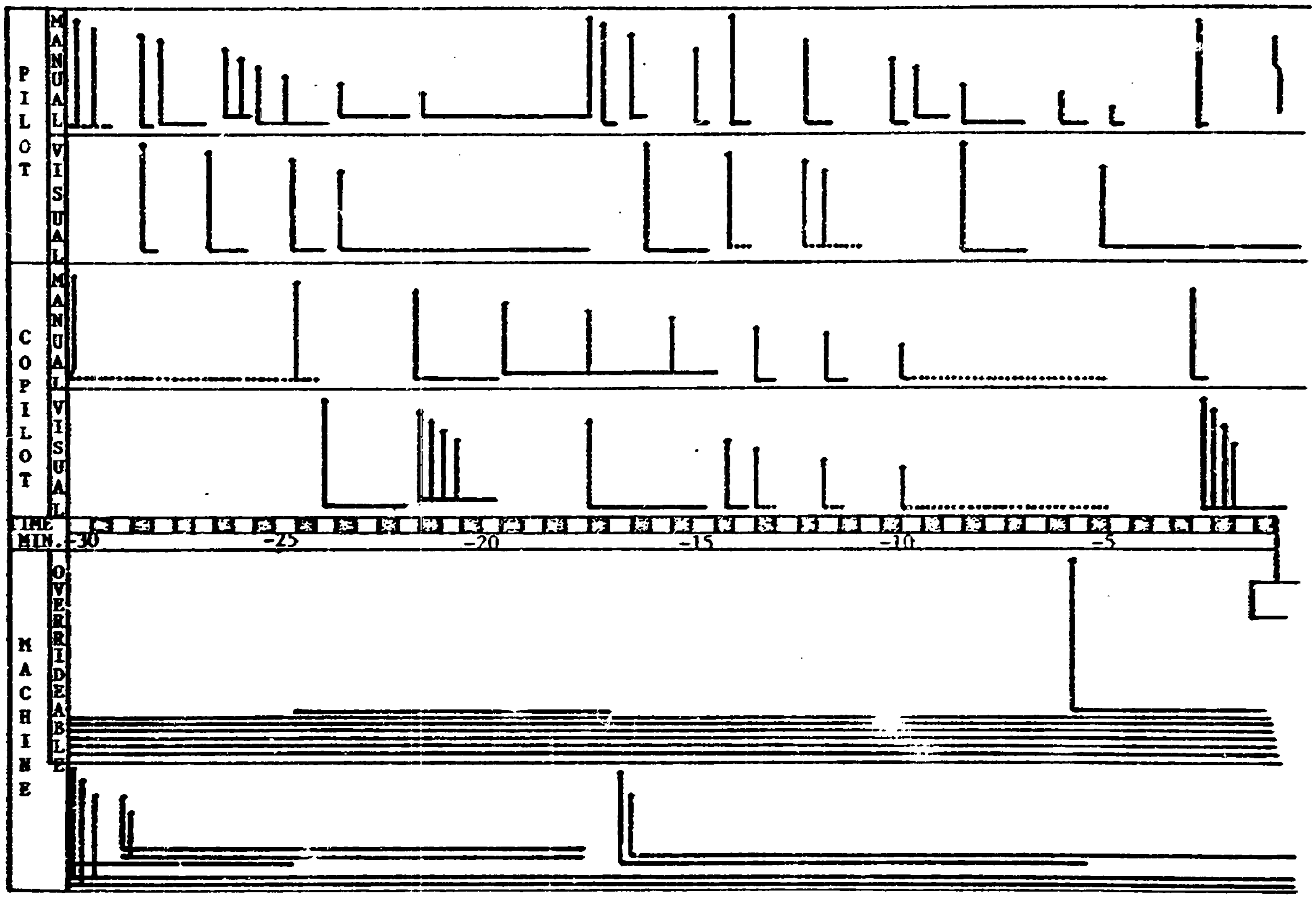


Figure 2 Typical Time Line Task Assignment Chart (Re-entry Phase Section)

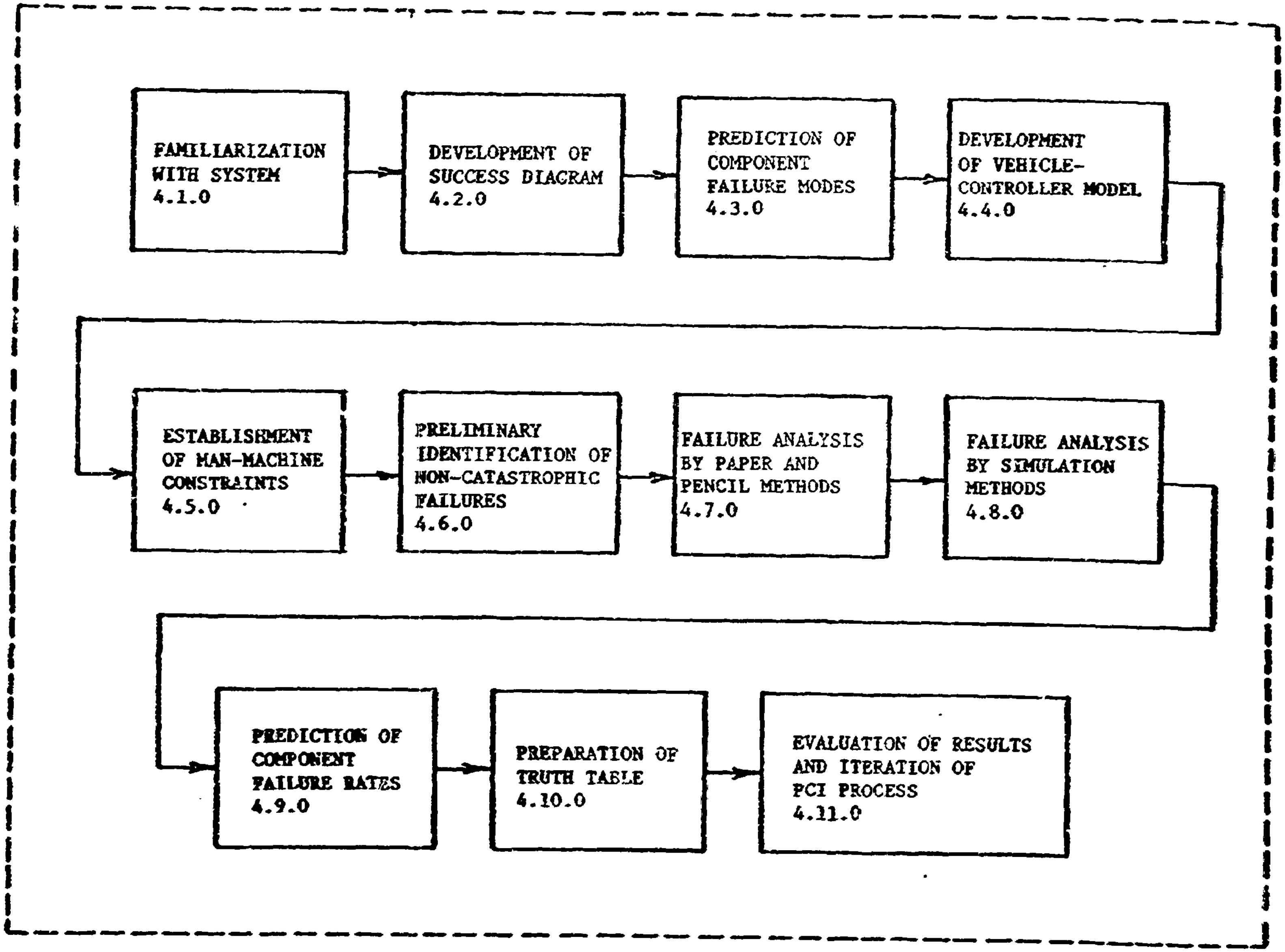


Figure 3 Phases of PCI Process

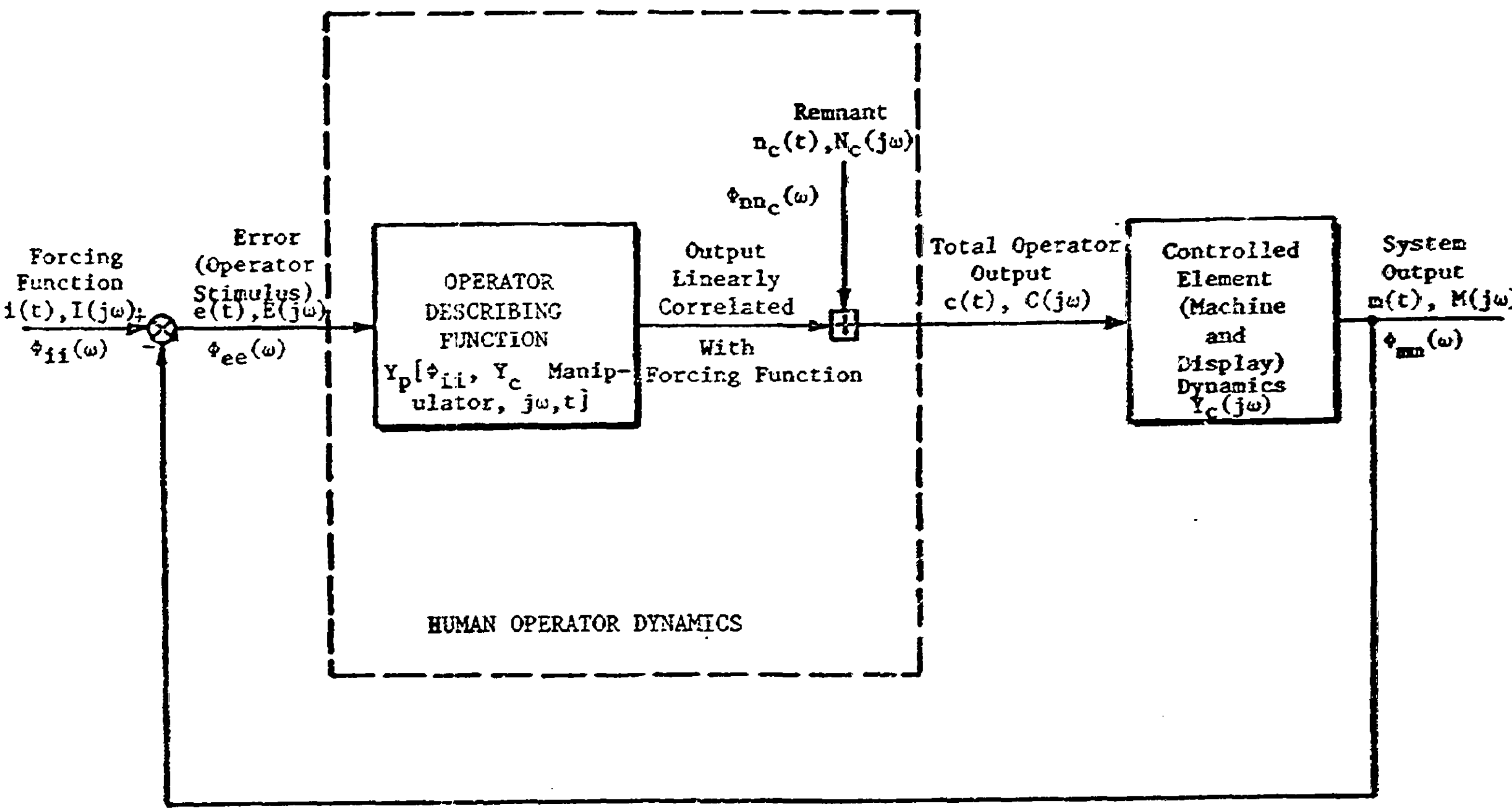


Figure 4 Equivalent Block Diagram of the Human Operator in a Compensatory Tracking Task

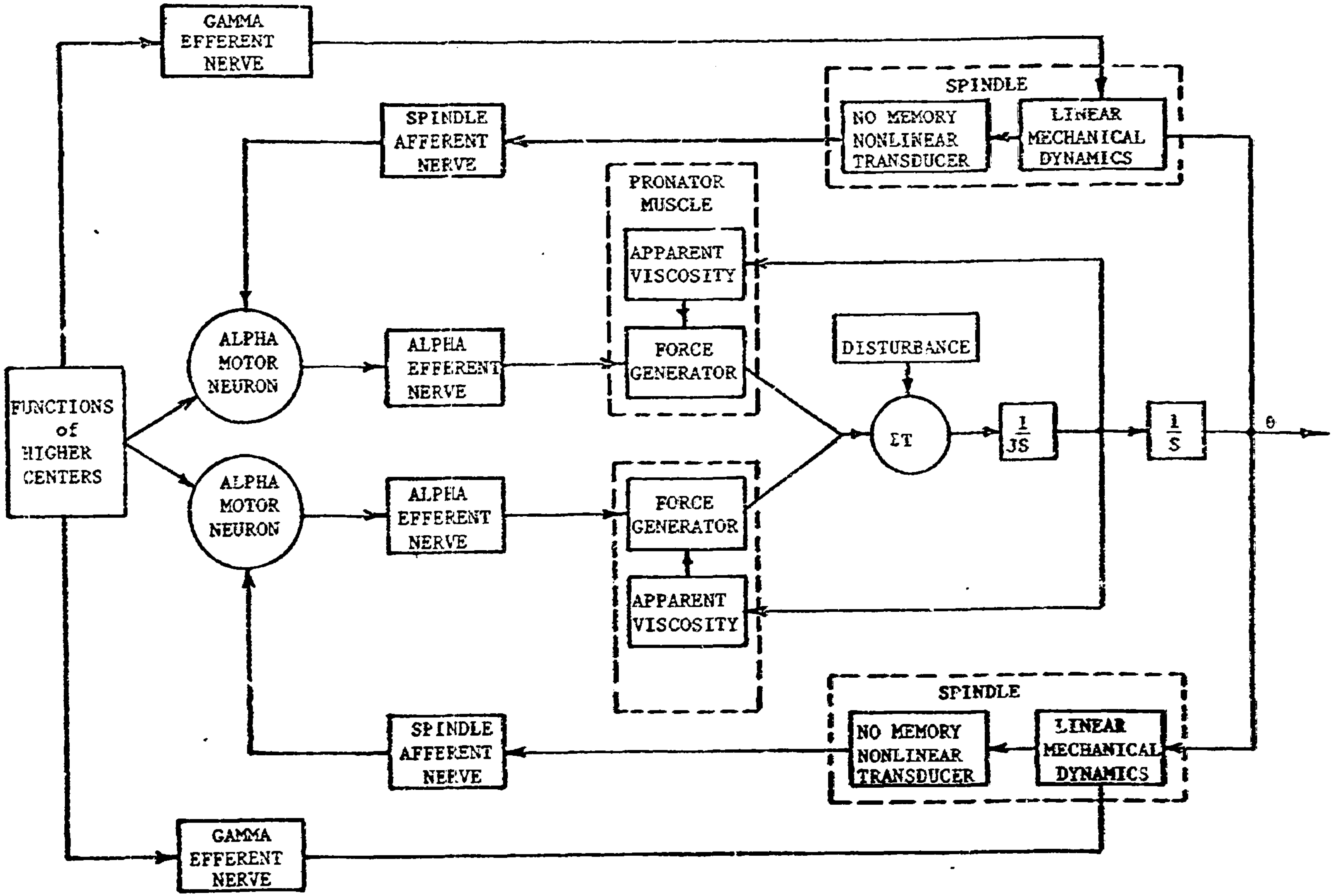


Figure 5 Block Diagram Of The Control System For Hand Movement

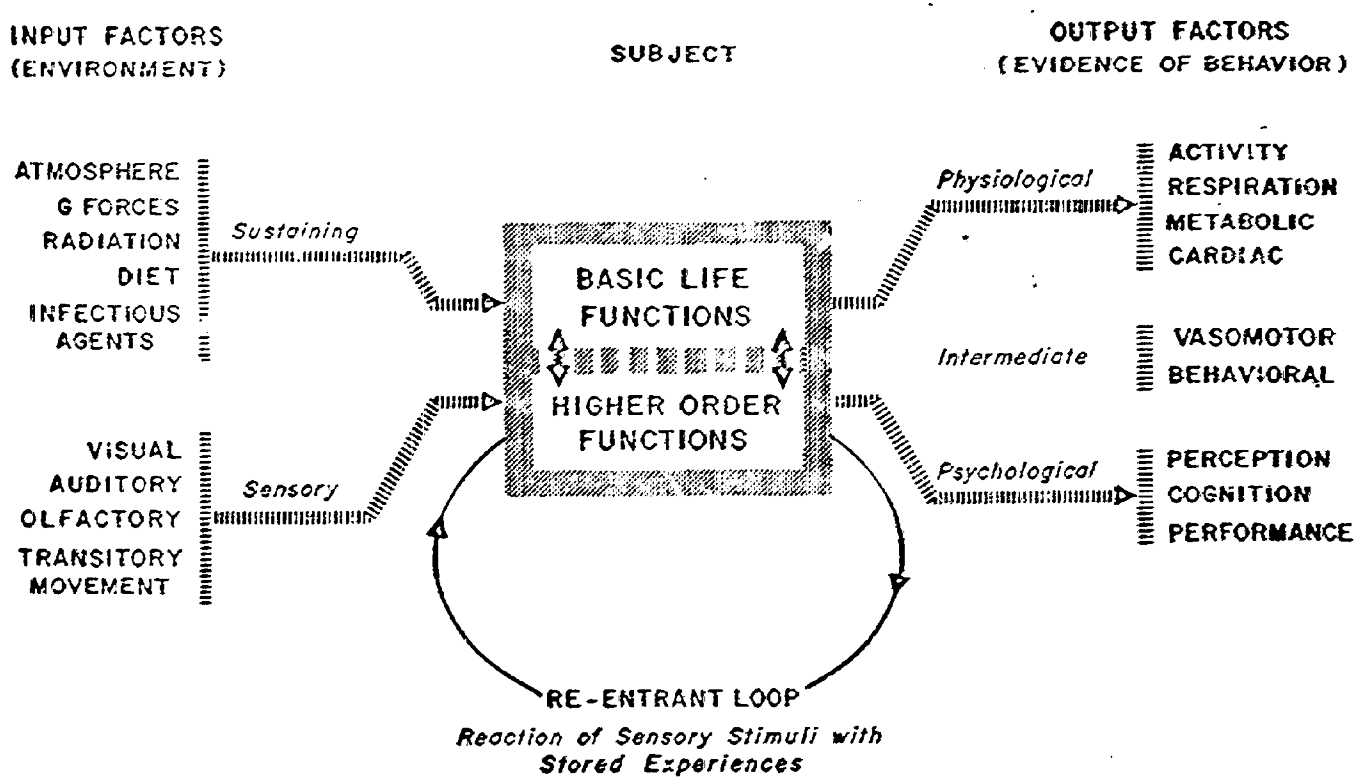


Figure 6 Factors Involved in Physiological Measurements

Multiplication Problem	Average Percent Change in Pupil Size
7 X 8	10.7
8 X 13	11.8
13 X 14	19.3
16 X 23	22.3

Figure 7 Pupil Size Variation in Problem Solving

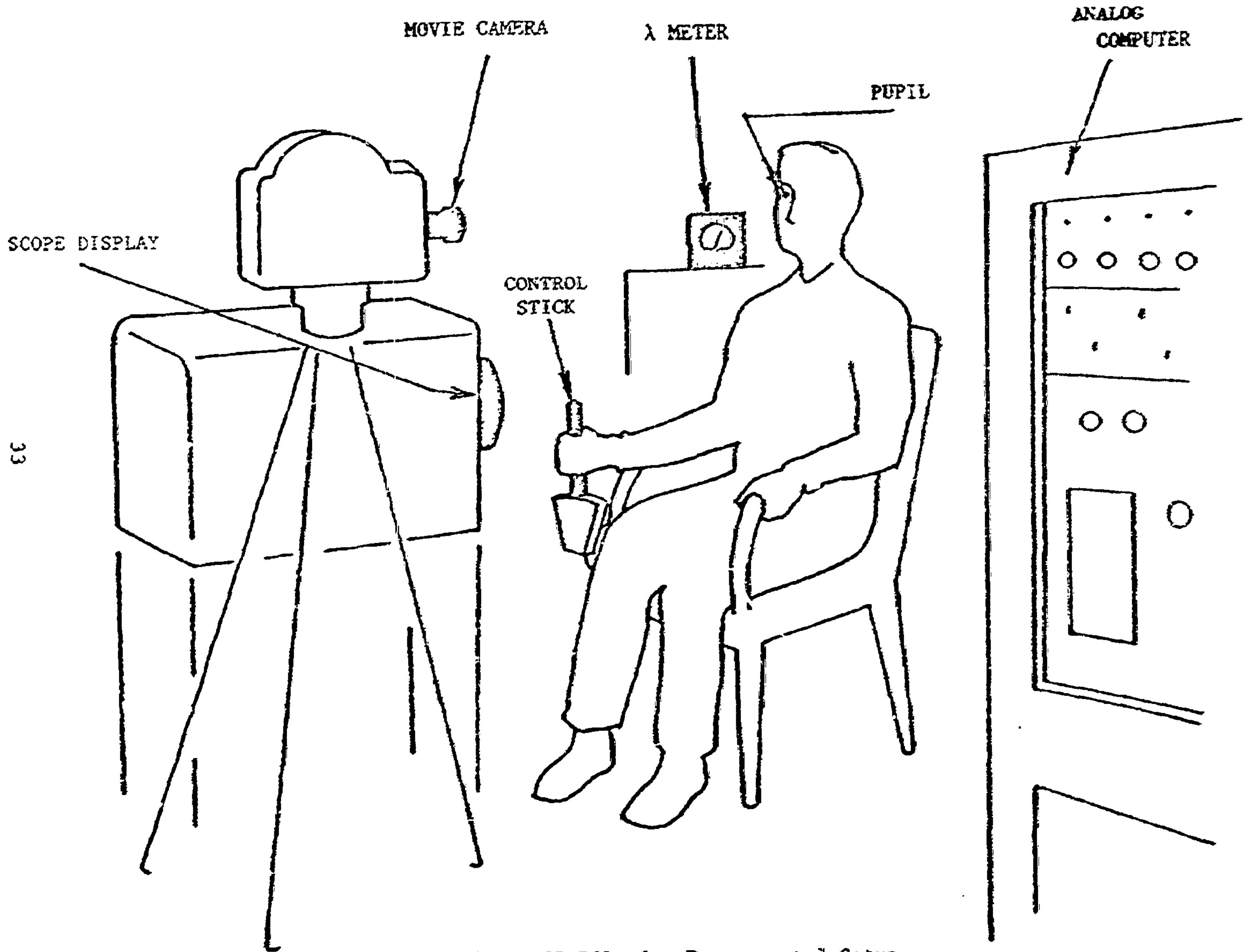


Figure 8 Pupil Dilation Experimental Setup

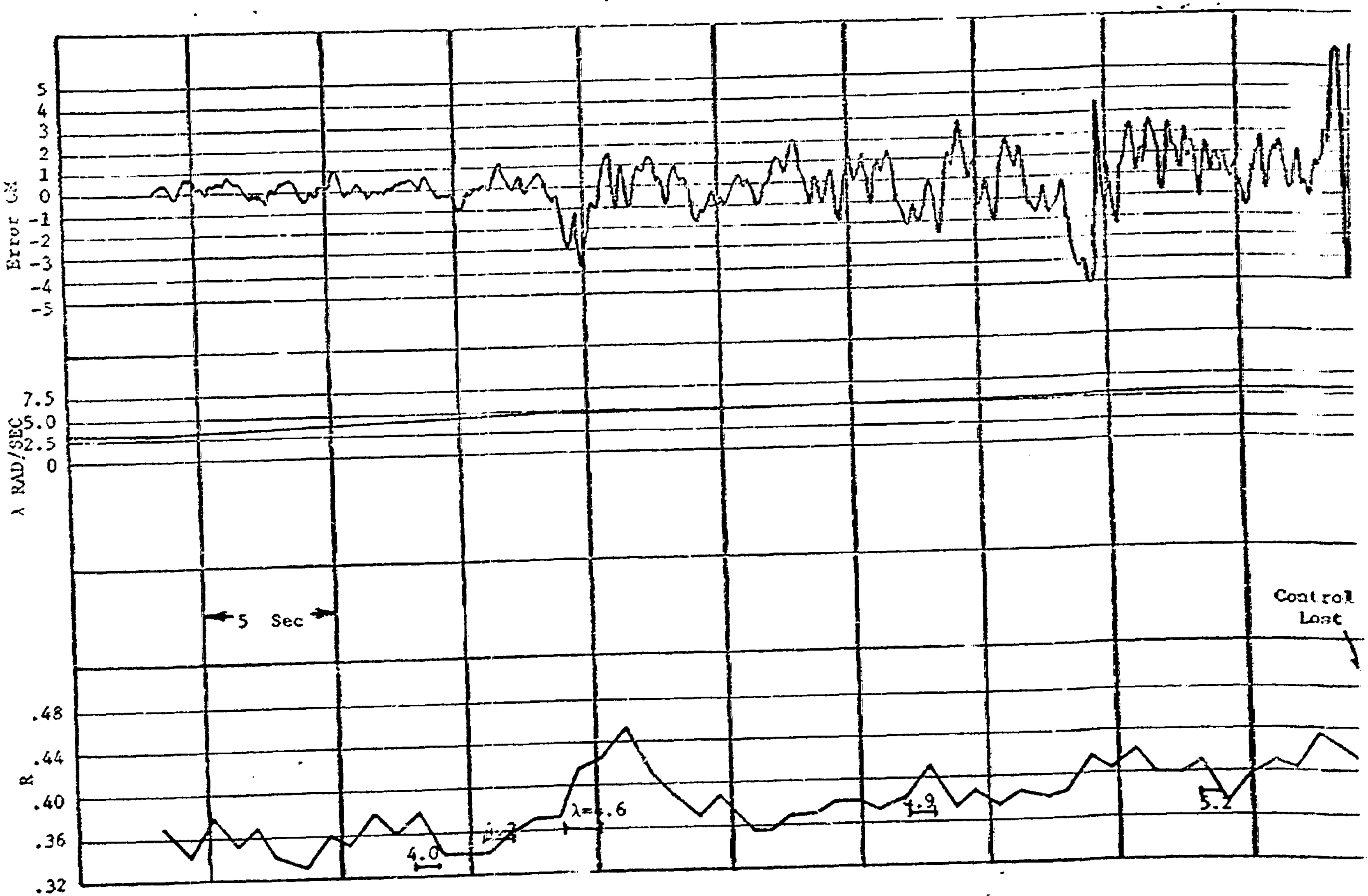


Figure 9 Results of Time-Varying λ Experiment

λ (rad/sec)	R (Nondimensional)	T (sec)
4.0	.33	.65
4.3	.35	.69
4.6	.36	.93
4.9	.37	1.08
5.2	.38	.98
5.5	.37	1.00
5.8	.40	.89
6.0	.42	.81

Figure 10 Correlation of Workload and Pupil Dilation

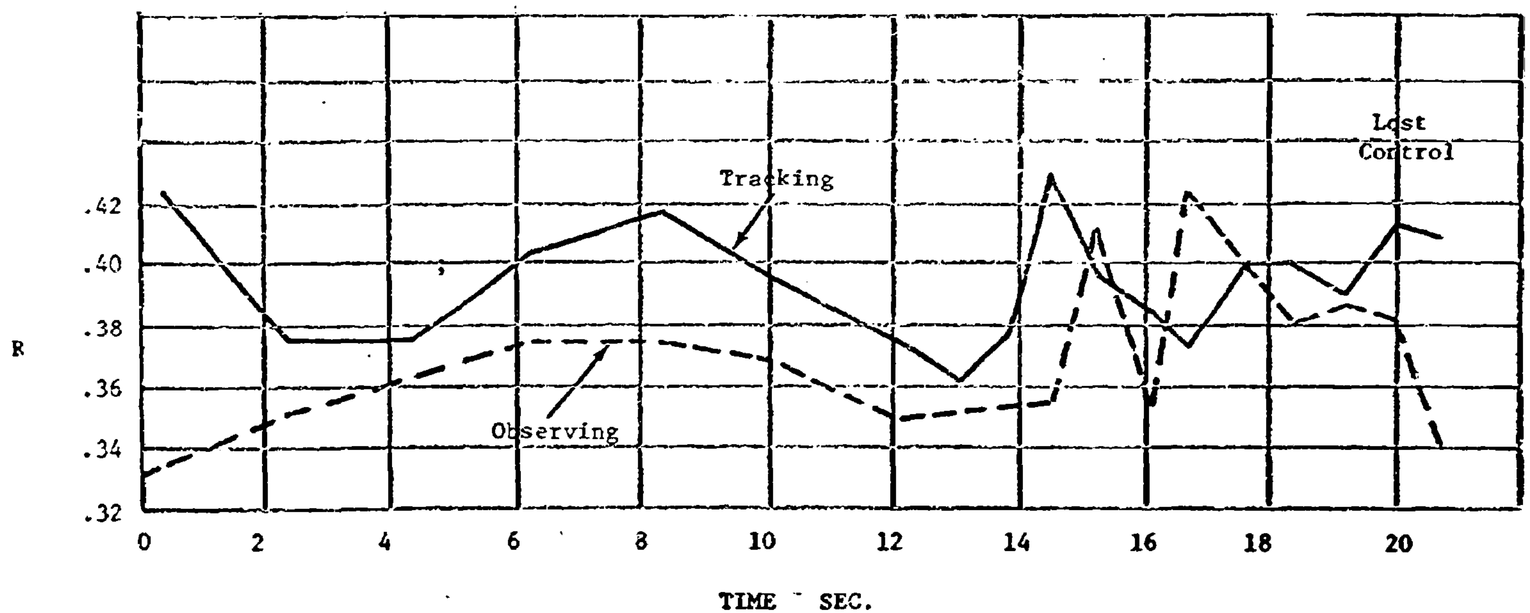


Figure 11 Pupil Variations in Tracking Vs. Error Observation